...r of *Spheres of unequal size widely spaced* (Fig. 64).

$$C = \frac{1{\cdot}11 r_1 r_2 d}{(r_1 + r_2)d - 2r_1 r_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (50)$$

r_1 and r_2 are the radii of the two spheres.
d is their separation (measured between their centres).

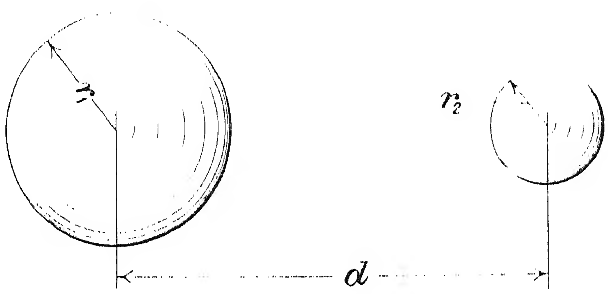

FIG. 64. TWO WIDELY-SPACED SPHERES OF UNEQUAL SIZE

...r of *Spheres of equal size, close together* (Fig. 65).

$$C = 0{\cdot}556r\left(1 + \frac{x}{6r}\right)\left(1{\cdot}2704 + \tfrac{1}{2}\log_e \frac{r}{x} + \frac{x}{18r}\right) \quad . \quad (51)$$

x is the distance between the nearest points of the spheres
r is their radius.

...TE. This formula gives results correct within 0·1 per ...when x/r is less than 0·1.)

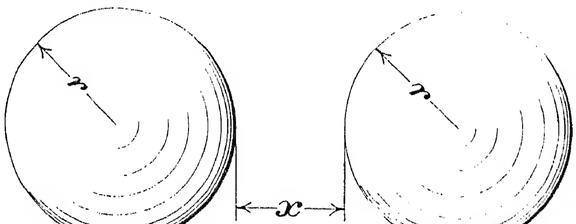

FIG. 65. PAIR OF SPHERES OF EQUAL SIZE CLOSE TOGETHER

Joint Capacity of two equal spheres, close together ... in space (Fig. 66).

$$C = 1{\cdot}11r\left(1 + \frac{x}{6r}\right)\left(1{\cdot}3863 - \frac{x}{12r}\right) \quad . \quad .$$

where x and r have the same significance as in form...

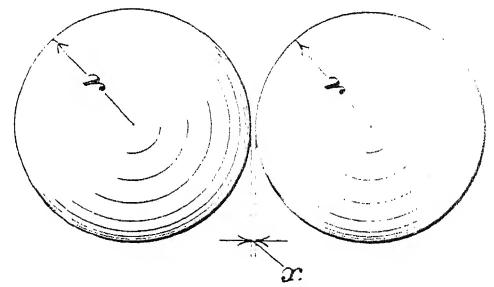

FIG. 66. TWO EQUAL SPHERES CLOSE TOGETHER

Joint Capacity of two spheres of very unequal size and isolated in space (Fig. 67).

$$C = 1{\cdot}11r_1\left(1 + 2{\cdot}404\frac{r_2^{\,3}}{r_1^{\,3}}\right) \quad . \quad . \quad . \quad .$$

where r_1 is the radius of the larger sphere.
r_2 is the radius of the smaller sphere.

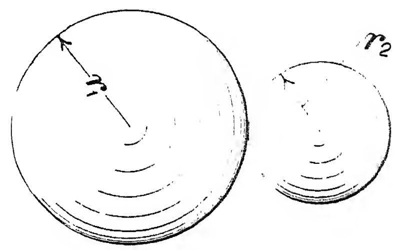

FIG. 67. TWO UNEQUAL SPHERES IN CONTACT

Sphere and Plane (of large area) (Fig. 68).

$$C = 1{\cdot}11rh\,(h - r) \quad . \quad . \quad . \quad . \quad .$$

ELECTRICAL CONDENSERS

ELECTRICAL CONDENSERS

THEIR CONSTRUCTION, DESIGN AND INDUSTRIAL USES

BY

PHILIP R. COURSEY

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LONDON
SIR ISAAC PITMAN & SONS, LTD.
PARKER STREET, KINGSWAY, W.C.2
BATH, MELBOURNE, TORONTO, NEW YORK
1927

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PRINTED IN GREAT BRITAIN
AT THE PITMAN PRESS, BATH

PREFACE

ALTHOUGH the first electrical condenser was discovered nearly two centuries ago, it is only during the last two or three decades that any real progress has been made in the practical utilization of condensers. During the intervening period condensers were regarded at first only as scientific toys; while later they became purely physical laboratory apparatus. The commercial development of condensers has been slow, due perhaps in part to the above causes, and even to-day, in many quarters, condensers are still looked upon to a great extent as frail scientific instruments which cannot possibly have any serious industrial uses. There are, however, many practical applications of condensers which are growing rapidly in importance, and it is the purpose of this book to endeavour to dispel this feeling by describing the modern developments which have taken place in condensers, by illustrating their methods of manufacture on a considerable scale, and by detailing many of their present and possible future industrial applications.

The fundamental nature of condensers is described in Chapter I, and from their very general nature it follows that very many practical forms of construction are possible. These various forms have different applications, the form very largely depending upon the nature of use. The origin of some of these forms, as resulting from the early discoveries and history of condensers, may be traced in Chapter II, which describes the principal discoveries and experiments of the early days of condensers, and deals also with the development of various theories for explaining condenser action, and the phenomena observed in various dielectrics used in condensers.

Radio telegraphy—and more recently, radio broadcasting—has until recently constituted the most important application of condensers, and has been directly responsible itself for the development of certain forms of condenser, some of which have moreover now become almost obsolete. Air, glass, and mica,

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The special applications of certain dielectrics to modern electrical condensers are dealt with in Chapters XIII to XVIII, wherein many forms of such condensers utilizing air, glass, oil, paper, mica, and "cellon" dielectrics, are described and illustrated. The chief uses to which these types of condensers are applied are also dealt with, including high-tension electric power circuits (Chapter XVIII) and power-factor improvement (Chapter XIX). Various other applications are described and possible developments foreshadowed in Chapter XX, and the volume is concluded with an extensive Bibliography relating to dielectrics and to condensers, which includes a list of British patents on the same subjects, and relating thereto, which it is hoped is complete up to the present date.

The voluminous literature relating to dielectrics precludes the possibility of including all references which might be of some interest in connection with this subject, but it is hoped that the majority of the articles and publications of importance have been mentioned. Notification of any omissions or corrections to this section will be particularly welcomed from readers. In many cases the references given include abstract references to *Science Abstracts*, or other publications wherein similar abstracts appear, as it is felt that by this means searching in the literature of a subject is facilitated.

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The many modern uses of condensers in connection with radio apparatus are classified in Chapter VIII, in accordance with the nature of the voltages and electric stresses applied to the condensers, and typical forms of condensers for such uses are described and illustrated.

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as well as to manufacturers and others engaged in the industry. The growing demand for condensers of various types emphasizes the need for further research and development and, to those engaged in this work, it is hoped that this book will especially appeal.

My acknowledgments and best thanks are due to many friends and firms who have assisted in the preparation of the book, and who have supplied photographs and other data, and permission to publish some of the information contained in this book. Amongst these, the following may be specially mentioned: Messrs. Autoveyors, Ltd.; Bowyer-Lowe Co., Ltd.; Brittains, Ltd.; Burndept Wireless, Ltd.; Cambridge Instrument Co., Ltd.; De Laval-Chadburn Co., Ltd.; Dubilier Condenser Co., Ltd.; Electric Furnace Co., Ltd.; Gambrell Bros., Ltd.; General Electric Co., Ltd.; Gesellschaft für drahtlose Telegraphie, m.b.H. (Berlin); Iliffe & Sons, Ltd.; International General Electric Co.; Isenthal & Co.; Marconi's Wireless Telegraph Co., Ltd.; Marconiphone Co., Ltd.; Metro-Vick Supplies, Ltd.; Mullard's Radio Valve Co., Ltd.; Ormond Engineering Co., Ltd.; Radio Communication Co., Ltd.; Société Anonyme des Condensateurs de Trévoux; Société Générale des Condensateurs, Fribourg (Suisse); Société Générale des Condensateurs et Appareils de Protection Électrique (Paris); H. Tinsley & Co.; C. A. Vandervell & Co.; Westinghouse Brake and Saxby Signal Co., Ltd.; Weston Electrical Instrument Co., Ltd.; and E. H. Shaughnessy, Esq. Also to my wife for her untiring help in the preparation of the Bibliographical and other sections of this book, and in the preparation of it for the press.

PHILIP R. COURSEY

RICHMOND, SURREY
June, 1926

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ELECTRICAL CONDENSERS

CHAPTER I

THE NATURE AND FUNDAMENTAL PROPERTIES OF CONDENSERS

THE word "condenser" as applied to a certain piece of e
trical apparatus, has during the past few years become one
popular and everyday use. Prior to the use of radio appara
on a large scale for broadcast reception, the word was kno
only as referring to a certain type of scientific instrume
and by a comparatively few engineers concerned with
employment of "condensers" in certain radio and in spe
commercial applications. Radio broadcasting is thus prima
responsible for the popularization of this and of many anot
apparatus which would otherwise in all probability not h
emerged from the laboratory for many more years to come

These remarks apply mainly to certain specific types
"condensers" which have especial application in radio rece
ing apparatus; but it is no less true to say that the devel
ments which have taken place in radio communication meth
generally during the past decade, have equally been respons
in great degree for the developments in other classes and ty
of electrical "condensers." This statement is not meant
imply that condensers had no commercial or industrial ap
cations prior to the above-mentioned developments, for s
is far from the case, but by the application of these devel
ments not only may the article employed in known uses
improved, but new uses may be created for the impro
articles thus produced.

In the case of the development of "condensers" brou
about by the demands of radio communication, not only

the increased demand for a certain class of apparatus been productive of improved manufacturing methods, but as a secondary result of that demand, a much augmented financial expenditure has been possible on research work dealing with the scientific problems associated with the development of other classes of "condensers" and of "dielectrics" for use in "condensers."

"What is an Electrical Condenser?" The multitudinous forms in which condensers are constructed, and the very many purposes for which they may be used, render a very precise definition of the word somewhat difficult, especially as many modern applications of condensers make use of properties which were not suspected when condensers were first discovered. Expressing it in quite general terms, it may be stated that "anything in or on which an electric charge can be stored, may be called a 'condenser.'" In practical everyday use, however, the word "condenser" is given a much more restricted meaning, and is applied only to definite pieces of electrical apparatus in which, by their design, the property of storing electric charges has been concentrated as much as possible.

Another and older definition has been expressed as follows: "A condenser consists of a conductor, or conductors, arranged to have a specially large capacity." This, as will be shown later, is merely another way of expressing the generalized definition set out in the preceding paragraph, and while this is really a true definition if applied to all the parts or elements of a condenser, it does not at first sight appear to apply in the strict sense to many modern forms of condensers, in which for certain electrical reasons the capacity is small, although the physical bulk is large.

There is, as will be shown later, some connection between the storage of an electric charge, and the storage of electrical *energy*, and as a result, a better definition of a condenser can be expressed in terms of such energy storage as follows—

A condenser consists of a dielectric bounded by two conductors insulated from one another, the capacity for storing electrical energy being large for the volume of dielectric employed.

The "dielectric" referred to in this definition is an essential part of every electrical condenser, and is the part of the condeners which is mainly responsible for the properties of the condenser itself. The term is due to Faraday who coined it in connection with his fundamental researches into the nature of dielectric action.

For a proper appreciation of the true nature of a condenser, and of the part played by the dielectric in forming a condenser, it is essential to consider first the most elementary form of condenser and the mode in which it acts. The form in which the action of condensers was first discovered—the Leyden jar (see Chapter II)—is not, perhaps, the simplest type of condenser, but, taken in conjunction with the ideas of those days and with other apparatus used at that time, it provided the name "Condenser"—a name which has persisted until to-day, in spite of the very many varieties now known. and in spite of the fact that it is really a misnomer.

The early theories of electricity, current in the latter half of the eighteenth and part of the nineteenth centuries, considered electricity to consist of either one or of two fluids—fluids which could not be seen or weighed, but which made their presence felt in the various electrical phenomena then known. It was found possible to store up the "electric fluid" in a glass bottle filled with water, and hence what more natural name for this device than an electrical "condenser." These old fluid theories have long since gone by the board, and have been replaced by the electron theory, hinted at by Clerk Maxwell in 1873, and later developed by G. J. Stoney ([5]) and others ([3] and [12]).*

The electron may be termed the atom of electricity, and modern views hold that every atom of matter has a number of electrons as part of its structure. Every electron has the same negative charge,† and hence, when an electron is removed from an atom, the effect produced is that of a positive charge on the atom.

* These numbers refer to the numbered Bibliography to be found at the end of the volume

† The terms positive and negative, as applied to electric charges, were first fixed in a quite arbitrary manner.

The electron theory may be said to have resulted from many different lines of scientific inquiry and research. Of these, three may perhaps be mentioned: Electrolytic action; electro-optical effects; and the phenomena of electrical discharges through rarefied gases. The laws of electrolysis, discovered by Faraday, pointed directly to an atomic constitution for electricity, for they showed that each chemical atom, of whatever its nature, always transported a definite quantity of electricity or an integral multiple of that quantity. Maxwell's electromagnetic theory of light suggested that all material particles carry electric charges, and Zeeman's discovery in 1896 of the change of frequency of lines in the spectrum when the light source was subjected to a magnetic field, provided a confirmation of this hypothesis. Probably the most striking verifications of the actual physical existence of electrons have been furnished by experiments on electric discharges in partially exhausted bulbs. Crooke's experiments, conducted between 1875 and 1890 made visible the effects of streams of electrons passing through rarefied gases; and the subsequent researches in particular by Sir J. J. Thomson and Sir Ernest Rutherford have enabled many of the properties of electrons and of the chemical atoms and ions to be investigated.

The ratio of the electric charge to the mass of an electron has been found by such experiments to be about 18,000,000, whereas the corresponding ratio for hydrogen, which is the lightest known chemical atom, is only 9577. If, then, the hydrogen ion in electrolysis carries the same charge as one electron, as has been demonstrated in other ways, it follows that the electron must be a very much lighter particle than the hydrogen atom. The ratio of the above quantities indicates that its weight is approximately $\frac{1}{1845}$ of that of the hydrogen atom. The mass of the electron is, however, thought to be entirely electromagnetic in nature, and therefore to depend upon the speed with which the electron moves through the ether.* Quite recently, Sir Oliver Lodge (9)† has suggested

* The ether is the name given to the imponderable material which is assumed to fill all space and all substances. It is the medium through which electric fields and electric waves are transmitted.

† These numbers refer to the numbered Bibliography to be found at the

that an electron may really be merely a species of " hole " or " bubble " in the universal aether, and that the aether removed from the centre of the electron and concentrated in the interior of the positive residuum of the atom from which an electron has been removed, may explain the large mass of the atom as compared with the electron. This, however, is at present merely speculation—and awaits definite proof or disproof as the case may be.

The extreme lightness of the electron explains the fact that even the addition of very large numbers of electrons in a charge given to a piece of metal, does not appreciably alter the weight of that material. We can only detect the presence of electric charges on materials by the electrical effects set up, and not by any mechanical or visual change in the material. Usually these effects occur only between two pieces of material or matter carrying electrical charges ; and these effects in fact are largely the basis of condenser action as will now be explained more fully.

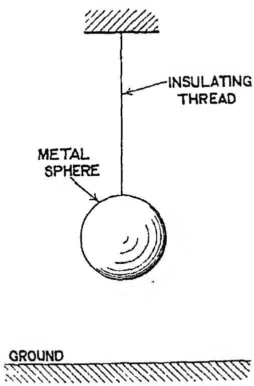

Fig. 1. An Insulated Metal Sphere forming a Simple Condenser

A negative electric charge is given to a substance when it is given an excess of electrons ; and a positive charge when some electrons are removed, leaving less than the normal number. In materials which can conduct electricity readily—e.g. most metals—a certain number of electrons are free to move about under the influence of any electric force which may be applied to them, but some always remain bound to the atoms and cannot be removed unless the atom is broken up or dissociated. In other substances—i.e. electrical insulators—there are very few free electrons, and these can only move about in the material with very great difficulty.

If a piece of metal—say, for example, a sphere (Fig. 1)—is suspended by an insulating thread, so that electrons are prevented from moving on to or off the sphere (the air

surrounding the sphere is also an insulator), the arrangement constitutes a very elementary condenser. If an electric charge, consisting of a huge crowd of electrons, is put on to the sphere by some suitable means, the nature of which is immaterial for the purposes of the present argument, it will not be able to escape from the sphere owing to the insulation. The sphere thus becomes a means of storing an electric charge.

The quantity of electricity which can be stored on this metal sphere is somewhat limited, depending upon the size of the sphere, and upon its distance from other objects. The ability of the sphere to store the electric charge is referred to as its *capacity*. The *capacity* of any condenser may thus be regarded as a measure of its electrical size.

Since all electrons carry the same charge, of the same sign, they all repel one another, and it follows necessarily that work must be done to bring electrons near to one another against this repulsive force. In other words, to increase the electric charge on the above sphere some work must be expended. This factor then sets some limit to the amount of the charge which can be put on to the sphere.

Then, again, owing to this repulsive force, the electrons will spread themselves over the surface area of the sphere and will not be distributed throughout the interior. The effect of this repulsive force may be likened to an " electronic pressure " tending to force the electrons out of the metal. Since the surrounding air is an insulator, the electrons cannot escape, unless the electronic pressure becomes very great, when ultimately the air will break down, and a spark will pierce it. This is what occurs when a lightning flash passes from a cloud to the earth, the coalescence of raindrops in the cloud gradually concentrating the electrons and increasing the pressure—or, as it is called in electrical parlance, the *voltage*—until the spark passes and some electrons escape.

Obviously, the bigger the sphere, the more electrons can be crowded on to it before the voltage (or pressure) is raised to a given amount, or in other words, the *capacity* of a larger sphere for storing electrons, is greater. There is, in fact, a simple relation between these three quantities, the capacity

being defined as the quotient of the charge by the voltage. Hence, the unit of capacity is defined as the capacity of a condenser such that the addition of unit charge to it raises the voltage to unity.

Expressing this definition in everyday electrical units, it may be written—

> A condenser has unit capacity when a charge of one coulomb raises its potential to one volt.

This unit is called the *farad*, named after Michael Faraday, who carried out much of the original research work on the phenomena associated with condensers.

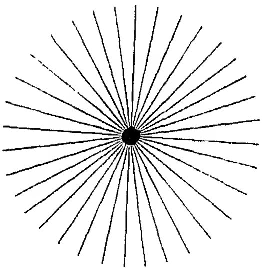

FIG. 2.
FIELD OF ELECTRIC LINES OF FORCE ROUND AN ELECTRON

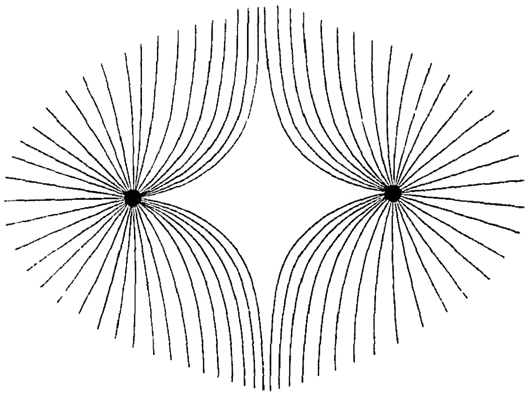

FIG. 3. REPULSION OF LINES OF ELECTRIC FORCE BETWEEN TWO ELECTRONS

In metals, and all electrical conductors, electrons are free to move about under the action of the forces naturally existing between them and of any external forces. If electrons are added to one part of a conductor, and are left to themselves, they will immediately distribute themselves over the entire metal surface by virtue of the repulsive action between them. In electrical insulators, electrons are not free to move, and consequently, if some are added to one part of an insulator they will not be able to distribute themselves over the material, but will remain in a more or less concentrated condition. If left for prolonged periods, a redistribution of electrons over the surface of an insulator will usually take place, as no insulator

is quite perfect, but can conduct to a very slight extent. The fact that two charges of opposite sign (positive and negative) can exist simultaneously on an insulator without mixing, explains the name bestowed upon such materials—viz. *dielectric*. This name was given by Faraday, who first investigated their properties ([14]).*

The field of force which surrounds each electron may be visualized by imagining a series of electric *lines of force* radiating from every electron (Fig. 2). These lines, if they commence at an electron, must all terminate on a positive charge, and by assuming that such lines are like strings of elastic, always tending to shorten themselves, the attraction between positive and negative charges can be visualized. Likewise, if these lines mutually repel one another, the field of repulsive force between two electrons can likewise be pictured (Fig. 3).

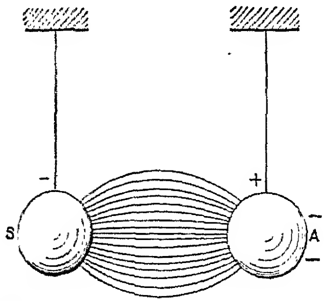

Fig. 4. Lines of Electric Force Between Charged and Uncharged Spheres

Bearing this in mind, it becomes possible to explain what occurs when another insulated conductor is brought up into the neighbourhood of the charged sphere which has already been discussed. Such a second conductor is sketched at A in Fig. 4. If the sphere S is charged with electrons, the electric lines of force radiating from it will repel the free electrons, in the second sphere A, as far away as possible from the first sphere, and the lines of force between the spheres will end on the resulting positive charges on the side of A nearest to S. These positive charges will result from the removal of electrons from this face of the sphere, due to the repulsive action of the electrons on S, leaving positively charged atoms or "ions." The second conductor will thus have induced in it the two charges, positive and negative, these being kept apart by the field due to the charge on S.

* See also Chapter II

The proximity of the induced positive charge on A will concentrate the electric field, and will increase the effective capacity of the first sphere, since a greater charge can be put on to S than before, without raising its voltage to a higher value. The capacity of the condenser formed by S and A will therefore be greater than the capacity of the single sphere S by itself.

The nearer together that the two spheres are brought, the greater will become the concentration of electrons on the side of S nearest to A, leaving the opposite face of S freer of electrons, and therefore able to receive more. The capacity of the condenser formed by the two spheres S and A is therefore a function of the spacing between the spheres, increasing as this spacing is reduced. This relation is considered in detail for various specific forms of condensers in Chapter VI.

As far as the action of the condenser formed by the two spheres in Fig. 4 is concerned, the presence of the induced negative charge on the sphere A, consisting of the electrons which have been repelled to the part of the surface farthest from S, is not necessary. In the actual case sketched in Fig. 4, the presence of this induced negative charge will somewhat modify the electric field between the two spheres, and therefore will have some slight influence upon the effective electrical capacity of these spheres. Under normal conditions one sphere would have a negative charge, and the other a positive charge only.

In essential form, therefore, an electrical condenser has three parts—two metallic, or at least electrically conducting, parts which serve as the electrodes on to which the electric charges can be put; and an electrical insulator, or dielectric separating the two conductors. In practical constructions of condensers, as will be described in later chapters of this volume, other subsidiary parts become necessary, such, for example, as parts to support and hold the essential elements of the condenser, boxes or cases to contain these parts, and special insulators to support and hold terminal bolts to which external conductors can be connected to enable the condenser to be joined into the electrical circuit in which it is to be used.

In Fig. 4, the two spheres S and A constitute the two conductors of the condenser, and the air separating them is the electrical insulator or dielectric. While this pair of spheres, therefore, exhibits the essential features of a condenser, the arrangement would not ordinarily be termed a condenser, since as has already been explained, the name is generally reserved for definite pieces of apparatus. Two spheres suspended by threads, is scarcely a sufficiently rigid or definite construction to come within the scope of this definition.

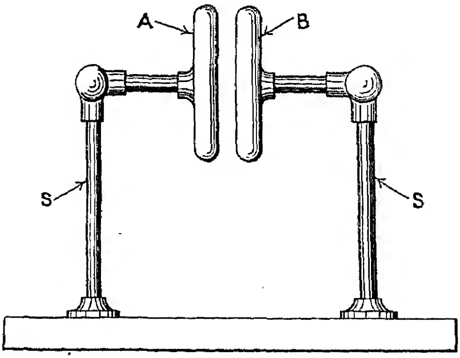

Fig. 5. A Simple Air Condenser

A simple form that complies with this definition of a condenser is sketched in Fig. 5. It consists of two metal discs, A and B, supported parallel to each other by means of insulating rods SS, which may conveniently be made of glass, or ebonite, or other equivalent good electrical insulator. A form of condenser similar to this was used a great deal in many of the early experiments on electrostatics carried out many years ago by the early workers in this field.

The two discs may be charged up by pumping electrons into one of them, from some convenient source (the nature of which is immaterial at present). and so giving that one a negative charge ; and extracting a like number of electrons from the other, and so giving that one a positive charge. These two charges will be equal in magnitude, and either of them may be denoted by the algebraic symbol Q. The presence of these charges on the two discs will give rise to a potential difference between them, which is defined as the work required to be expended to move a unit electric charge from one disc to the other, against the forces exerted by the charges on the discs. This potential difference may be denoted by the symbol V.

The capacity of the condenser formed by the two discs is then defined, as has already been indicated in general terms, by the following relation, denoting this capacity by the symbol C—

$$C = Q/V \quad . \quad . \quad . \quad . \quad . \qquad (1)$$

Hence, the unit of capacity, known as the *farad*, may be defined as the capacity of a condenser such that a charge of one *coulomb* of electricity is required to produce a difference of potential of one *volt* between its terminals.

In practical use the *farad* as a unit is inconveniently large, and a subdivision of it is customarily employed, known as the *microfarad*, and having a value of one-millionth of a farad. This unit serves for all ordinary uses, but for still greater convenience in radio work it has become customary to subdivide still further this unit into another, again one-millionth of it in value, and known as the *micromicrofarad*. When this unit is used the capacities of most condensers used in radio circuits are expressible in figures between zero and about 5000, and consequently the advantage is secured of the elimination of the continual use of a decimal fraction to denote the capacities commonly in use.

For many industrial, as well as some radio uses, the microfarad as a unit meets all requirements, the capacities then being expressible in quantities lying between about one-hundredth of a microfarad and a few microfarads usually not exceeding a few hundred.

To summarize the relationship between these units—

1 farad = fundamental unit of capacity entering into most formulae.

1 microfarad = 0·000001 farad.

1 micromicrofarad = 0·000001 microfarad
= 0·000000000001 farad.

The letter C, printed in italic type, has been standardized internationally as a symbol for representing capacity in mathematical formulae; and the letter F, printed in roman type, is likewise standardized to represent the above-mentioned unit of capacity, the farad. The prefix μ (Greek letter " mu ") is

employed as the standard abbreviation for the fraction of one-millionth, so that the unit called the microfarad can be represented by the symbol μF. Similarly the micromicrofarad unit is written $\mu\mu$F.

Occasionally, also, the prefix symbol m, meaning "milli," or one-thousandth, is employed in connection with condensers. Thus mF stands as a symbol for a unit which may be termed the millifarad (0·001F); and mμF for the millimicrofarad (0·000000001F). These two subsidiary units, however, are very rarely used.*

From a further consideration of the simple condenser that has been sketched in Fig. 5, it is possible to derive an expression for the energy that is stored up in a condenser when an electric charge is given to it. As has already been mentioned, the potential difference V between the two discs is defined as the work that must be done to move a unit electric charge from one disc to the other. Hence, if a small quantity of electric charge represented by the symbol δQ is imagined as being transferred from one disc to the other against the force due to the potentials of the discs, the work that must be done to effect this transfer is $V\delta Q$. To effect the transfer of the entire charge Q from one disc to the other—such as would be a means of establishing the electric field between the two discs in the first instance—the work that must be done is

$$\int_0^Q V dQ$$

* Certain other abbreviated prefixes and symbols are also in common use, based on international agreements. These will be employed throughout this book in connection mainly with other electrical units, viz. resistance, voltage, current, etc.

Prefixes : μ = micro- (one millionth)
m = milli- (one thousandth)
k = kilo- (one thousand times)
M = meg- or mega- (one million times)

Symbols : F = Farad (unit of capacity) general symbol C
H = Henry (unit of inductance), general symbol L
Ω = Ohm (unit of resistance), general symbol R
A = Ampere (unit of current), general symbol I
V = Volt (unit of voltage), general symbol V
Coulomb (unit of quantity or charge), general symbol Q

The relation between Q, V, and the capacity of C the con denser, has already been given, viz. $Q = CV$.

Hence, by substitution in the above integral, the total work to be done becomes

$$W = \int_0^Q V dQ = \int_0^Q (Q/C) dQ = \tfrac{1}{2}\, Q^2/C$$
$$= \tfrac{1}{2}\, CV^2 \qquad . \qquad . \qquad (2)$$

This expression therefore represents the work that must be expended to establish the electric field between the plates of the condenser, when it is charged up, and is consequently the energy stored up in the condenser when the field has been established.

To charge up a condenser, say, from a battery or other similar source of electrical energy, a current must flow into the con denser plates for a short period until the charges are established Expressed in terms of the electron theory, this current flow consists of the movement of electrons from the negative ter minal of the battery, which has a high electron pressure, into one of the plates of the condenser, which flow or movement wil continue until the potential difference between the plates o the condenser has risen to the same as that of the battery use to charge them. The movement of electrons into one of th plates will be accompanied by a corresponding movement ou of the other plate back into the positive pole of the battery Thus, to all apparent evidence, the charging up of the condense is accompanied by an apparent flow of current through th condenser for a very short period. The larger the capacit of the condenser, the greater the number of electrons tha must pass into the plates, and therefore the longer will th charging current persist before the condenser plates reach th same potential difference as that applied from the battery.

Likewise, when a condenser has been charged up and insu lated from the charging source, a discharge current can b drawn from it by connecting the two plates together throug a piece of wire. All the energy that has been stored up in th electric field between the condenser plates will be returne by the condenser by this discharge current. This energy